

Measurement of the CP Conserving Magnetic Dipole (M1) Direct Photon Emission and a Search for the CP Violating Electric Dipole (E1) Direct Photon Emission in the $K_L \rightarrow \pi^+\pi^-\gamma$ Decay Mode

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In this paper the KTeV collaboration reports the analysis of 111.4K $K_L \rightarrow \pi^+\pi^-\gamma$ decays. The amplitude for M1 direct photon emission and its associated vector form factor parameterized as $|\tilde{g}_{M1}|(1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma})$ have been measured to be $|\tilde{g}_{M1}| = 1.229 \pm 0.035(\text{stat}) \pm 0.087(\text{syst})$ and $a_1/a_2 = -0.733 \pm 0.007(\text{stat}) \pm 0.014(\text{syst}) \text{ GeV}^2/c^2$ respectively. In addition, we have conducted a search for the CP violating E1 direct photon emission, achieving an upper limit for the amplitude $|g_{E1}| \leq 0.14$ (90% CL). These measurements, together with the amplitude $|g_{BR}|$ for E1 inner bremsstrahlung photon emission (IB), yield a direct emission to total photon emission ratio $DE/(DE + IB) = 0.698^{+0.007}_{-0.012}$ averaged over the range of $E_\gamma \geq 20 \text{ MeV}$.

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The KTeV collaboration has reported a measurement [1] of a_1/a_2 of the M1 direct photon emission vector form factor as well as $DE/(DE + IB)$, the ratio of direct photon emission to total photon emission in the $K_L \rightarrow \pi^+\pi^-\gamma$ decay mode using data accumulated in the 1996 KTeV E832 run at Fermi National Accelerator Laboratory. The \tilde{g}_{M1} amplitude itself as well as a_1/a_2 have been measured by the KTeV E799 experiment using the $K_L \rightarrow \pi^+\pi^-e^+e^-$ mode [2,3]. A search for the CP violating E1 direct photon emission amplitude $|g_{E1}|$ has also been made in $K_L \rightarrow \pi^+\pi^-e^+e^-$ data [3]. In this paper are presented measurements of $|\tilde{g}_{M1}|$ and its vector form factor and the ratio $DE/(DE+IB)$ determined using the much larger complete KTeV E832 1997 $K_L \rightarrow \pi^+\pi^-\gamma$ data set. We also present the results of a search for the E1 photon direct emission in $K_L \rightarrow \pi^+\pi^-\gamma$.

We have analyzed the $K_L \rightarrow \pi^+\pi^-\gamma$ decay mode us-

ing the model of Ref. [4] which includes a dominant CP-conserving direct M1 photon emission amplitude as well as the CP-violating inner bremsstrahlung amplitude that proceeds via the initial CP violating decay of the K_L into $\pi^+\pi^-$ followed by one of the pions undergoing inner bremsstrahlung. There is also the possibility of a CP violating direct E1 photon emission amplitude. The differential decay rate in the two independent variables θ and E_γ is given according to Ref. [4] by

$$\frac{d\Gamma}{dE_\gamma d\cos\theta} = \left(\frac{E_\gamma}{8\pi M_K}\right)^3 \left(1 - \frac{4m_{\pi^2}}{M_{\pi\pi}^2}\right)^{\frac{3}{2}} \left(1 - \frac{2E_\gamma}{M_K}\right) \times \sin^2\theta [|E1_{BR} + E1_{direct}|^2 + |M1_{direct}|^2] \quad (1)$$

In this expression θ is the angle of the photon with respect to the π^+ in the $\pi^+\pi^-$ center of mass system and E_γ is

the photon energy in the K_L rest frame of the three body $K_L \rightarrow \pi^+\pi^-\gamma$ decay. In addition,

$$E1_{BR} = \left(\frac{2M_K}{E_\gamma}\right)^2 \frac{g_{BR}}{1 - \left(1 - \frac{4m_\pi^2}{M_{\pi\pi}^2}\right)\cos^2\theta}$$

$$E1_{direct} = g_{E1}$$

$$M1_{direct} = g_{M1}$$

The amplitudes g_{BR} , g_{M1} , and g_{E1} are given by

$$g_{BR} = \eta_+ e^{i\delta_0(s=M_K^2)}$$

$$g_{E1} = \tilde{g}_{E1} e^{i\delta_1(s=M_{\pi\pi}^2)}$$

$$g_{M1} = \tilde{g}_{M1} \left(1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma}\right) e^{i\delta_1(s=M_{\pi\pi}^2)}$$

where the vector form factor associated with the $M1_{direct}$ amplitude has been parameterized using the formulation of Ref. [5]. Here M_ρ is the mass of the ρ meson (770 MeV/ c^2).

Note that in the differential cross section there is no interference term between the $E1$ and $M1$ amplitudes. However, there can still be an interference term in the differential cross section between the $E1_{BR}$ and $E1_{direct}$ amplitudes. The interference between the $E1$ bremsstrahlung and the $E1$ direct emission amplitudes will generate a contribution to the E_γ energy spectrum intermediate in energy between the lower energy bremsstrahlung photons and the higher energy $M1$ photons. Finally, note that unlike the $K_L \rightarrow \pi^+\pi^-e^+e^-$ decay there is no “charge radius” amplitude contribution [6–8] to the $K_L \rightarrow \pi^+\pi^-\gamma$ mode.

The $K_L \rightarrow \pi^+\pi^-\gamma$ signal of 111.4K events (above a background of 671 ± 41 events), obtained after the analysis cuts described below, is shown in Fig. 1. These $K_L \rightarrow \pi^+\pi^-\gamma$ data were accumulated during the 1997 run of the KTeV E832 experiment. In the 1997 run, a proton beam with intensity typically approximately 5×10^{12} protons per 20 second spill every minute, incident at an angle of 4.8 mr on a BeO target, produced two nearly parallel K_L beams, one of which intercepted a K_s regenerator and the other of which remained a “vacuum” beam. The data for the $K_L \rightarrow \pi^+\pi^-\gamma$ measurement were obtained from the “vacuum” beam decays. The momentum spectrum of the vacuum beam was determined using the $K_L \rightarrow \pi^+\pi^-$ two body decay data. The configuration of the KTeV E832 vacuum beam and spectrometer consisted of a vacuum decay tube, a magnetic spectrometer with four drift chambers, photon vetoes, a CsI electromagnetic calorimeter, and a muon detector. The spectrometer is more completely described in Ref. [9].

Approximately 4.3×10^8 $K_L \rightarrow \pi^+\pi^-\gamma$ candidates were extracted from the KTeV two track triggers [9] by requiring events with two tracks to pass track quality

cuts, have a common vertex with a good vertex χ^2 , and contain photons with $E_\gamma \geq 20$ MeV in the $\pi^+\pi^-\gamma$ rest frame. The tracks were also required to have opposite charges and $E/p \leq 0.85$, where E was the energy deposited by the track in the CsI, and p was the momentum obtained from magnetic deflection.

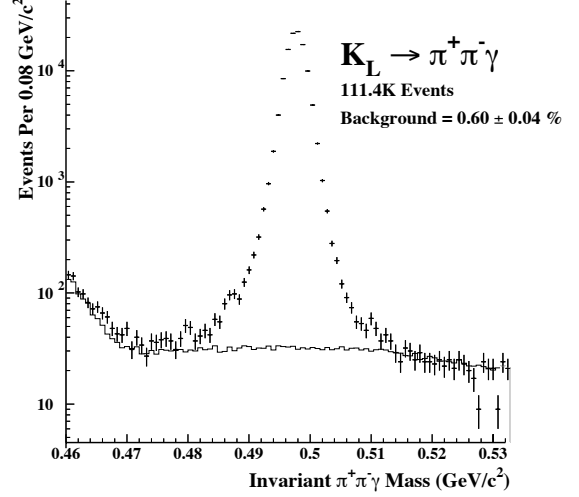


FIG. 1. $\pi^+\pi^-\gamma$ invariant mass for events passing all $K_L \rightarrow \pi^+\pi^-\gamma$ physics cuts. Crosses are data and the solid line is the fit to the background components

To further select the $K_L \rightarrow \pi^+\pi^-\gamma$ events and reduce backgrounds arising from other types of K_L decays in which decay products have been missed, the candidate $\pi^+\pi^-\gamma$'s were required to have transverse momentum P_t^2 relative to the direction of the K_L be less than 2.5×10^{-4} GeV $^2/c^2$. This cut was 94% efficient for retaining $K_L \rightarrow \pi^+\pi^-\gamma$.

The major background to the $K_L \rightarrow \pi^+\pi^-\gamma$ mode was due to accidental photon coincidences with $K_L \rightarrow \pi^\pm e^\mp \nu$ in which the electron was misidentified as a pion. This background was suppressed by electron E/p identification and P_t^2 and $M_{\pi\pi\gamma}$ mass cuts. An analogous background was due to $K_L \rightarrow \pi^\pm \mu^\mp \nu$ decays in which there was an accidental photon and the muon was misidentified as a pion. This background was suppressed by the muon detector identification as well as the P_t^2 and $M_{\pi\pi\gamma}$ mass cuts. The $\pi^+\pi^-\gamma$ background distributions due to the K_{e3} and $K_{\mu 3}$ decays were similar.

Another significant background to the $K_L \rightarrow \pi^+\pi^-\gamma$ mode was $K_L \rightarrow \pi^+\pi^-\pi^0$ in which one of the photons from the π^0 decay was not detected in the CsI calorimeter or the photon vetoes. To reduce this background, all $K_L \rightarrow \pi^+\pi^-\gamma$ candidate events were interpreted as $K_L \rightarrow \pi^+\pi^-\pi^0$ decays. Under this assumption, the longitudinal momentum squared $(P_L^2)_{\pi^0}$ of the assumed π^0 can be calculated in the frame in which the momentum of $\pi^+\pi^-$ is transverse to the K_L direction. $(P_L^2)_{\pi^0}$ was

mostly greater than zero for $K_L \rightarrow \pi^+\pi^-\pi^0$ decays except for cases where finite detector resolution resulted in a $(P_L^2)_{\pi^0} \leq 0$. In contrast, most of the $K_L \rightarrow \pi^+\pi^-\gamma$ decays had $(P_L^2)_{\pi^0} \leq 0$. The requirement that all $\pi^+\pi^-\gamma$'s had $-0.10 \leq (P_L^2)_{\pi^0} \leq -0.0055 \text{ GeV}^2/c^2$, together with the P_t^2 and $M_{\pi\pi\gamma}$ mass cut effectively suppressed this background.

Finally, hyperon decays such as $\Lambda \rightarrow p\pi^-$ decays plus an accidental photon with the proton misidentified as a π^+ or $\Xi \rightarrow \Lambda\pi^0$ decays with a misidentified proton and one of the π^0 photons missed were considered and determined to contribute approximately 5 events of background in the kaon mass region, a negligible contribution. Other minor sources of background such as $K_L \rightarrow \pi^+\pi^-$ decay coincident with an accidental photon or $K_S \rightarrow \pi^+\pi^-\gamma$ produced in the neutral beam production target were found to result in less than 2 events of background in the kaon mass region.

The final requirement of the $K_L \rightarrow \pi^+\pi^-\gamma$ events was $490 \text{ MeV}/c^2 \leq M_{\pi\pi\gamma} \leq 506 \text{ MeV}/c^2$. The magnitude of the remanent background under the K_L peak was determined by a fit of the wing regions above and below the K_L mass peak to the $\pi^+\pi^-\gamma$ background distributions due to $K_L \rightarrow \pi^+\pi^-\pi^0$ and K_{l3} decays. The other decays were negligible and ignored in this fit which yielded a total background of 671 ± 41 events, 133 ± 31 events of which were due to the $K_L \rightarrow \pi^+\pi^-\pi^0$ decays and remaining 538 ± 28 due to the K_{e3} and $K_{\mu 3}$ decays, the vast majority of which were K_{e3} .

The 111.4K candidate $K_L \rightarrow \pi^+\pi^-\gamma$ decays were analyzed in a likelihood fit based on the matrix element of the model of Ref. [4]. This likelihood is a function of the two independent variables θ and E_γ , the values of the fit parameters a_1/a_2 , $|\tilde{g}_{M1}|$ and $|g_{E1}|$ and the nominal values from the PDG [10] for the other model parameters such as η_{+-} . The strong interaction phase shifts of the final state $\pi^+\pi^-$ system are taken from Ref. [11]. The likelihood was calculated using a Monte Carlo event sample generated with nominal values of the fit parameters, passed through the spectrometer and reconstructed, and then reweighted with a new set of fit parameters using the $K_L \rightarrow \pi^+\pi^-\gamma$ matrix element of Ref. [4].

The likelihood fits to the two independent variables $\cos\theta$ and E_γ are shown in Fig. 2a) and Fig. 2b) respectively. The best fit values (68% CL) obtained were $a_1/a_2 = (-0.740 \pm 0.007(\text{stat})) \text{ GeV}^2/c^2$, $|\tilde{g}_{M1}| = 1.19 \pm 0.04(\text{stat})$ with an upper limit (90% CL) for $|g_{E1}| \leq 0.09$ considering only statistical error.

Uncertainties in a_1/a_2 , $|\tilde{g}_{M1}|$ and $|g_{E1}|$ due to variation of physics cuts, including those on E/p , E_γ , p_t^2 , $P_{\pi^0}^2$, vertex z , as well as others in Table I used to isolate the signal mode and reduce backgrounds, were determined by varying these cuts over reasonable ranges and observing the variation of a_1/a_2 and $|\tilde{g}_{M1}|$. Systematics due to uncertainties in the K_L^0 momentum spectrum were determined by using the K_L^0 momentum spectrum ob-

tained using the $K_L^0 \rightarrow \pi^+\pi^-$ mode and adjusting it to agree with the spectrum observed in $K_L^0 \rightarrow \pi^+\pi^-\gamma$ after the likelihood fit was performed. Any difference between a_1/a_2 , $|\tilde{g}_{M1}|$ and $|g_{E1}|$ before and after the final adjustment were taken to be a systematic error. Systematics due to uncertainties of parameters such as η_{+-} , and the strong interaction phase shifts $\delta_{0,1}$ that were not determined by the fit were studied by varying each parameter over $\pm 1\sigma$ of their published values and observing the variation of a_1/a_2 and $|\tilde{g}_{M1}|$. Final overall systematic errors in a_1/a_2 and $|\tilde{g}_{M1}|$ were then obtained by adding the individual errors in quadrature. Table I below lists the results of these systematic studies.

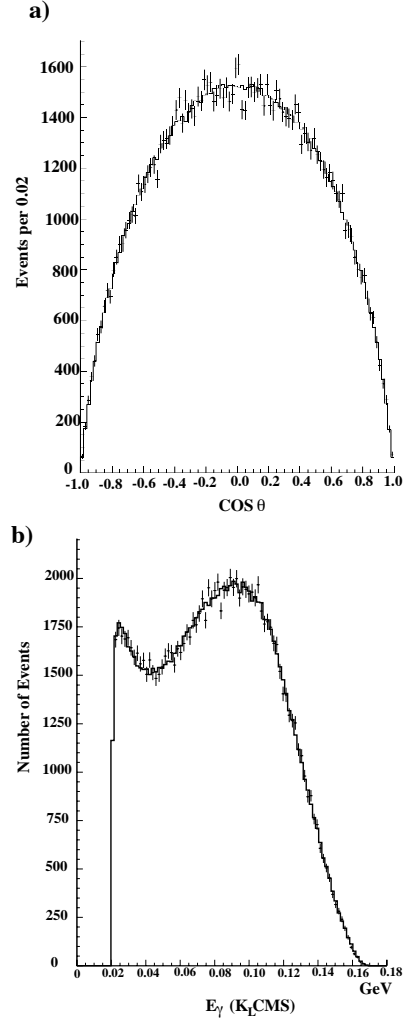


FIG. 2. Likelihood fit to the two independent variables in the K_L rest frame a) θ the angle between the π^+ and the γ in the $\pi^+\pi^-$ center of mass and b) the photon energy spectrum E_γ in the K_L rest frame

The results, including systematic errors of the measurement of the M1 direct photon emission amplitude and the attendant vector form factor, are $a_1/a_2 = (-0.733 \pm 0.0035(\text{stat}) \pm 0.087(\text{syst})) \text{ GeV}^2/c^2$ and

$|\tilde{g}_{M1}| = 1.229 \pm 0.035(\text{stat}) \pm 0.087(\text{syst})$. These measurements are in good agreement with the measurements of Ref. [1–3,12,13] (see Fig. 3). Finally, taking into account the systematic errors, an upper limit of $|g_{E1}| \leq 0.14$ (90% CL) was obtained.

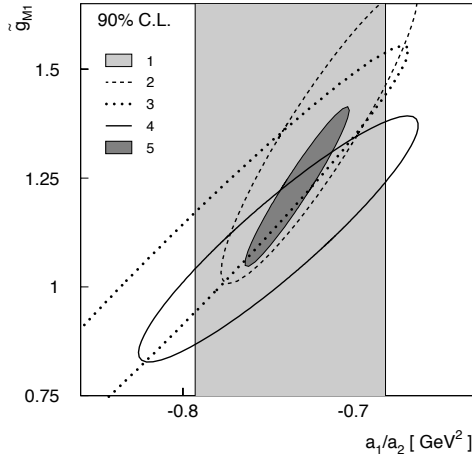


FIG. 3. 90% CL contours of \tilde{g}_{M1} vs. a_1/a_2 for various experimental measurements; results from the $K_L \rightarrow \pi^+\pi^-e^+e^-$ mode for NA48 data (3-dotted contour) of Ref. [12], for KTeV 97 data (2-dashed contour) in Ref. [2], and for KTeV 97+99 data (4-solid contour) of Ref. [13]; results from the $K_L \rightarrow \pi^+\pi^-\gamma$ mode from this paper (5-filled in contour), and for a_1/a_2 (1-light gray vertical region) from Ref. [1].

Using a_1/a_2 and $|\tilde{g}_{M1}|$ an average $\langle |g_{M1}| \rangle = 0.79^{+0.01}_{-0.02}$ over the range of E_γ was obtained. Using our measurements of $|\tilde{g}_{M1}|$ with its form factor and the bremsstrahlung amplitude $|g_{BR}|$ and taking $|g_{E1}|$ to be equal to zero, we have obtained the ratio of direct to total photon emission in $K_L \rightarrow \pi^+\pi^-\gamma$ decay to be $DE/(DE+IB) = 0.698^{+0.007}_{-0.012}$ for $E_\gamma \geq 20$ MeV. This result is consistent with the KTeV measurement of Ref. [1].

In conclusion, this paper has presented the best measurements achieved to date for the M1 direct photon emission form factor parameters $|\tilde{g}_{M1}|$ and a_1/a_2 . These measurements are consistent with our previous measurement of a_1/a_2 using the 1996 KTeV $K_L \rightarrow \pi^+\pi^-\gamma$ data [1] and with our measurements of $|\tilde{g}_{M1}|$ and a_1/a_2 using the 1997 and 99 KTeV $K_L \rightarrow \pi^+\pi^-e^+e^-$ data [2,3,13] and with the similar NA48 results [12] from $K_L \rightarrow \pi^+\pi^-e^+e^-$. In addition, we have determined an upper limit for CP violating E1 direct photon emission using the $K_L \rightarrow \pi^+\pi^-\gamma$ mode. This upper limit is consistent with the upper limit obtained using $K_L \rightarrow \pi^+\pi^-e^+e^-$ decays [3].

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| Source | $ \tilde{g}_{M1} $ | a_1/a_2 | $ g_{E1} $ |
|--|--------------------|-----------|------------|
| Baseline MC Bias | 0.0093 | 0.0021 | 0.013 |
| Kaon Beam Momentum Uncertainty | 0.0031 | 0.0004 | 0.005 |
| Background uncertainty | 0.0355 | 0.0067 | 0.045 |
| Overlapping clusters | - | - | - |
| Angular acceptance cut variation | - | - | - |
| p_t^2 cut variation | 0.012 | - | - |
| $P_{\pi^0}^2$ cut variation | - | - | - |
| Kaon momentum cut variation | 0.029 | - | - |
| Charged track/photon separation | - | - | - |
| Fluctuations during run | - | - | - |
| Vertex z cut variation | 0.034 | 0.0056 | - |
| $E_\gamma(\text{Lab})$ low cut variation | 0.054 | 0.0077 | - |
| E/p cut variation | - | - | - |
| K_S contamination | - | - | - |
| Fitting resolution | 0.014 | 0.0056 | 0.024 |
| $\omega, \cos\theta$ resolution | 0.023 | 0.0042 | 0.038 |
| η_{+-} uncertainty | 0.0171 | 0.0014 | - |
| δ_0 phase uncertainty | 0.0111 | 0.0021 | - |
| δ_1 phase uncertainty | 0.0053 | 0.0026 | 0.0348 |
| Total Systematic Error | 0.087 | 0.014 | 0.065 |

TABLE I. Syst. errors of a_1/a_2 , $|\tilde{g}_{M1}|$, and $|g_{E1}|$; where dashes are indicated, no uncertainty beyond statistical uncertainty in a_1/a_2 , $|\tilde{g}_{M1}|$, and $|g_{E1}|$ was caused by either cut variations or uncertainties in unfitted parameters. In the cases where systematic errors are given, variations in the parameters beyond statistical errors were observed.